Fuel Cell/Gas Turbine System Performance Studies

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Background

Because of the synergistic effects leading to the higher efficiencies and lower emissions achieved by combining a fuel cell and a gas turbine into a power generation system, many potential system configurations were studied by the Morgantown Energy Technology Center (METC) (1). Natural gas, indirect-fired, carbonate fuel cell bottomed, combined cycle (NG-IFCFC) and the topping natural gas/solid oxide fuel cell combined cycle (NG-SOFCCC) novel power plant systems were earlier introduced as high efficient systems. METC developed these systems for both the distributed power and on-site markets in the 20-200 megawatt (MW) size range. Most of these large fuel cell/gas turbine systems utilize a steam cycle to achieve high thermal efficiency. This work is focused on novel power plant systems by combining gas turbines, solid oxide fuel cells (SOFC), and a high temperature heat exchanger. These systems are ideal for the distributed power and on-site markets in the 1-5 MW size range.

Gas Turbine Configuration

METC developed a simple gas compressor-turbine (CT) system using the Advanced System for Process Engineering (ASPEN) computer simulator. This basic system consists of two gas turbines as shown in Figure 1. The first turbine drives the air stream compressors and the second turbine is used for power production only. For convenience, the first turbine is defined as a compressor-turbine and the second one a power-turbine. Low temperature combustors 870°C (1,600°F) are configured as topping combustors for both turbines. A recuperated-heat exchanger recovers waste heat from the power turbine exhaust. This recuperated thermal energy partially heats the compressor turbine inlet stream. Typical small recuperative gas turbine system parameters and design results are presented in Table 1. One advantage possessed by this system is that the low operating temperatures allow the design of a low-temperature turbine without blade cooling requirements and their associated costs. The electrical conversion efficiency of the CT system alone is greater than 40 percent on a net low heating value (LHV) basis (2,3).

Fuel Cell Configuration

The configuration, illustrated in Figure 2, is a generic system of a fuel cell bottomed by a heat recovery steam generator (HRSG) and a steam cycle. Fuel cells are electrochemical devices that oxidize fuel directly into electrical power without causing an excessive temperature rise, but oxidation of all the fuel is not complete inside the fuel cell. The remaining fuel oxidation also generates heat to raise the temperature of fuel cell exhaust that is then recovered in the HRSG.

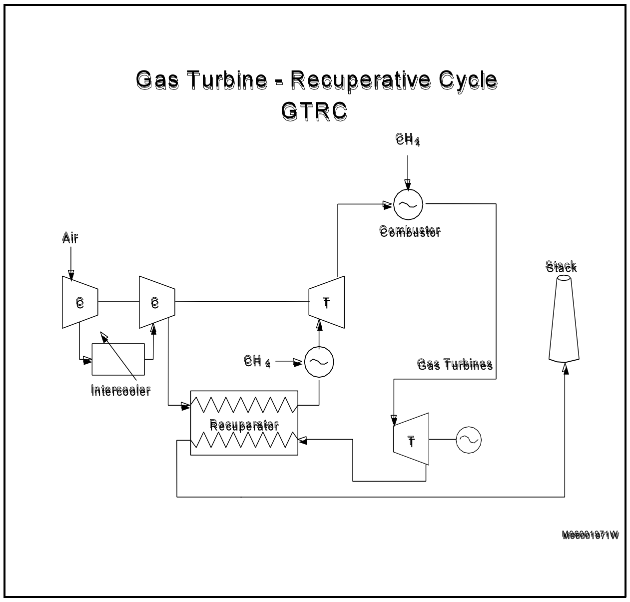

Figure 1. Gas Turbine Recuperative Cycle (GTRC)

Table 1. Gas Turbine Power Plant Performance (GTRC)

Compressor Air, lb/hr	40870
Turbine Fuel, lb/hr	510
CT Power, MW	1.3
Power Out, MW	1.4
System Efficiency, %LHV	42.9
Compression Ratio	8.8
Turbine Inlet, °F/°C	1580/860
Turbine Outlet, °F/°C	1180/638
Power Plant Exhaust,°F/°C	443/228

Thus, electrical energy and heat are both generated from the fuel cell. These large systems can obtain efficiencies greater than 65 percent (LHV) when coupled with an expensive HRSG and a steam turbine-based cycle. Performance results are presented in Table 2.

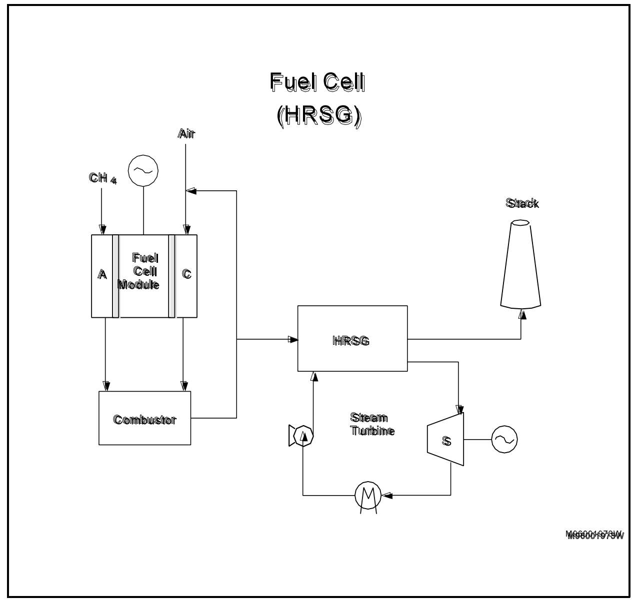

Figure 2. Fuel Cell — HRSG

Table 2. Fuel Cell Power Plant Performance

Fuel Cell Fuel, lb/hr	1165
Fuel Cell Power, MW	4.2
HRSG-Steam Cycle, MW	0.6
Power Out, MW	4.8
System Efficiency, %LHV	65
Power Plant Exhaust °F/°C	200/95

Fuel Cell/Gas Turbine Systems

Recently, development of small advanced gas turbines driven by low-inlet-temperature gas is underway (4). The use of a low-inlet-temperature gas turbine is advantageous: first, the turbines are manufactured using inexpensive construction materials and second, it synergistically matches the operating temperature of a fuel cell with the turbine inlet temperature. These small low-inlet-temperature recuperatored gas turbines can achieve high efficiency, greater than 40 percent cycle efficiency, on an (LHV) basis. In general, a molten carbonate fuel cell (MCFC) or a SOFC can achieve approximately 50 percent operating efficiency from fuel to electricity at atmospheric pressure. Current development of solid oxide fuel cells allows operation at pressures of 10-15 bar (10-15 atmospheres). Among the benefits of pressurization include improved cell performance, (i.e., increased power output), smaller equipment size, and reduced heat loss and pressure drops. The electric conversion efficiency increases several points due to the higher fuel cell operating pressure (5,6). Fuel cell thermal exhaust at 870°C serves as an excellent feed to the high-efficient, low-temperature gas turbine. Thus, the concept of a pressurized fuel cell topping a smaller gas turbine is born.

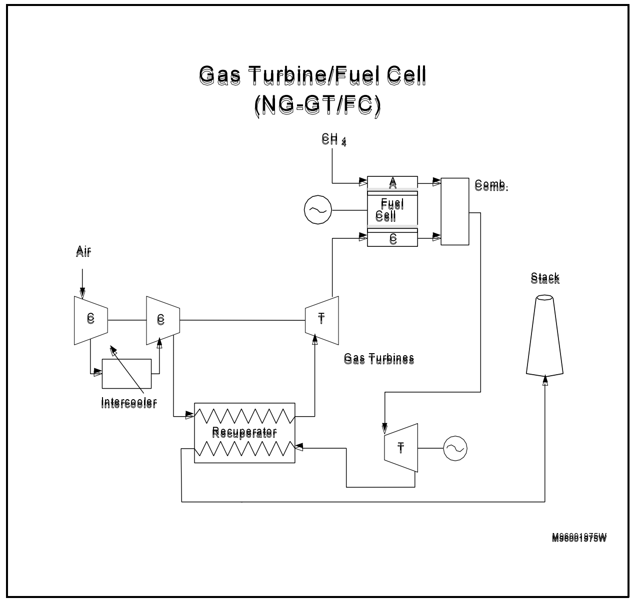

Figure 3. Gas Turbine/Fuel Cell (NG-GT/FC)

High pressure operation was not used in early fuel cells. This restricted the fuel cell operation compatibility with the low pressure power turbine. Even with the low pressure restrictions and inexpensive gas turbine components, simulation results indicate that system electrical conversion efficiencies can achieve 60 percent or more (LHV). Figure 3 shows a typical single fuel cell/gas turbine system configuration. The same shaft combustion turbine design provides a balance between electrical power output generated from the combustion turbine and the power requirement of the compressors. Net electrical output is generated from the low pressure (about three bar) fuel cell in series with the power turbine. Most of the fuel is introduced into the SOFC. About 50 percent of the chemical energy entering the fuel cell is converted to electrical power. Fuel cell exhaust gas expands through the second turbine in series with the fuel cell to generate additional power. Although the total fuel flow to the system increases, so does the total power output, therefore increasing the efficiency of the system. An ASPEN simulation projects system efficiency for the above simple systems approaching 62-68 percent on an (LHV) basis. These results are shown in Table 3. An alternative configuration is to move the single fuel cell and locate it before the compressor-turbine and the ASPEN simulation indicates similar results.

As fuel cell research progresses, high pressure fuel cells are becoming available. The system efficiency can be increased further by integrating a second fuel cell in front of the compressor-turbine. Integrating the processes, the fuel cell is used as a topping combustor to the compressor turbine. The topping fuel cell generates additional electrical power while providing a thermal exhaust at (870°C). The calculated fuel to electricity efficiencies are greater than 70 percent for the combined fuel cell/gas turbine system of 1-5 MW size (7,8). Figure 4 shows the dual fuel cell/gas turbine system configuration. System parameter

Table 3. Low Pressure Fuel Cell Power Plant Performance (NG-GT/FC)

Compressor Air, lb/hr	40870
Turbine Fuel, lb/hr	165
LP Fuel Cell Fuel, lb/hr	979
CT Power, MW	1.3
Fuel Cell Power, MW	3.1
Power Turbine, MW	1.5
Power Out, MW	4.6
System Efficiency, %LHV	64.4
Compression Ratio	8.8
Turbine Inlet, °F/°C	1580/860
C. Turbine Outlet, °F/°C	1178/637
P. Turbine Outlet, °F/°C	1204/651
Power Plant Exhaust, °F/°C	350/177

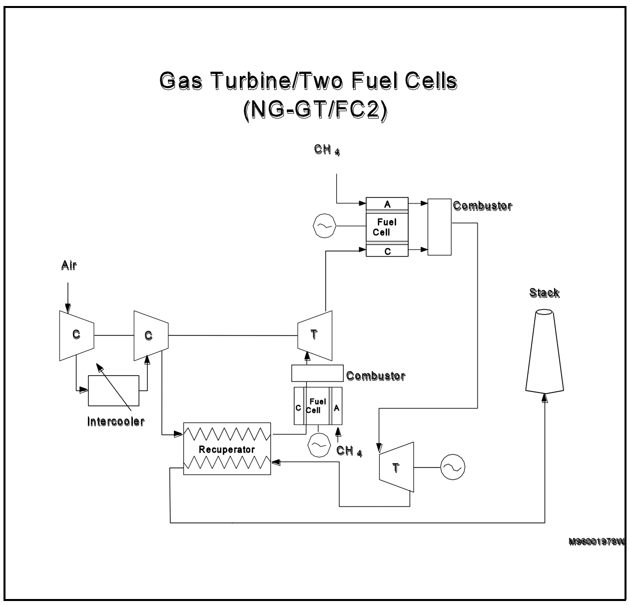

Figure 4. Gas Turbine/Two Fuel Cells (NG-GT/FC2)

values and ASPEN calculation results are shown in Table 4.

Table 4. Two Pressure Fuel Cell Power Plant Performance (NG-GT/FC2-5 MW)

Compressor Air, lb/hr	40870
LP Fuel Cell Fuel, lb/hr	630
HP Fuel Cell Fuel, lb/hr	750
CT Power, MW	1.3
Power Turbine, MW	1.5
LP Fuel Cell Power, MW	2.1
HP Fuel Cell Power, MW	2.6
Power Out, MW	6.2
System Efficiency, %LHV	71.9
Compression Ratio	8.8
Turbine Inlet, °F/°C	1580/860
Turbine Outlet, °F/°C	1200/649
Power Plant Exhaust, °F/°C	299/148

The small (1-5 MW) fuel cell and the fuel cell/gas turbine systems are ideal for distributed power generation. Distributed locations in residential areas are possible because of the environmentally clean and low noise characteristics of the fuel cell. Furthermore, the cost of the system is potentially lower than the fuel cell-steam cycle system, since the expensive steam cycle is replaced by a high efficiency gas turbine. A lower total system cost is the primary benefit obtained by coupling the fuel cell and gas turbine power generation systems. Labor costs are also lower because an operator is constantly required for steam turbines, while many states do not require an operator constantly on duty for gas turbines. The integrated fuel cell and gas turbine are well suited to accomplish this strategy, allowing for an early introduction of the technology.

Table 5 presents a summary of fuel to electrical efficiencies for current advanced power generating systems calculated by the

Table 5. Comparison of Power Generating Technologies

Efficiency	Technology Configuration	LHV %	HHV %
NG-IFCFC	GT-Fuel Cell-HRSG	74	67
NG-SOFCC	GT-Fuel Cell-HRSG	74	67
NG-GT/ FC2-5MW	GT/2 Fuel Cell	72	65
NG-GT/FC	GT/Fuel Cell	65	60
MCFC-ST	Fuel Cell-HRSG	65	60
SOFC-ST	Fuel Cell-HRSG	63	58
ATS utility	Adv. Gas Turb-HRSG	62	56
GTCC-200 MW	Gas Turbine-HRSG	56	51
GTRC- 5 MW	Gas Turbine/ Recup C	43	40
PC/FGD	Pulverised Coal/FGD	--	35

ASPEN simulator. A quick comparison suggests that the fuel cell/gas turbine system is twice as efficient as the baseline pulverized coal power plant, reducing fuel consumption and CO_2 emissions by 50 percent.

Summary

ASPEN simulations of power generation systems indicate potential advantages of developing a fuel cells/gas turbine system without a steam cycle. The synergistic effects could improve electrical conversion efficiencies to greater than 70 percent (LHV). Also, it simultaneously reduces fuel consumption and environmental emissions by 50 percent when compared to the baseline standard pulverized coal-fired power plant.

The 5 MW system size is ideal for distributed power generation. Additionally, the capital and life costs of the fuel cell/gas turbine system are potentially lower than a basic fuel cell or fuel cell-steam turbine system, because some power is produced by a simple-cycle gas turbine.

Further development and acceptance of this combined system allows a fuel cell to be introduced to the market along with a gas turbine having a high response, low cost, and fuel flexibility. The gas turbine is provided the opportunity to expand into environmental markets in non-attainment areas and meet stringent emission regulations. Table 6 summarizes the advantages of the fuel cell/gas turbine power generation system.

Table 6. Advantages of Fuel Cell/Gas Turbine Technologies

System has lower capital costs and life costs than FC + ST.
Near constant efficiency over a wide temperature range.
Low temperature turbine operation results in no blade cooling.
Ideal size for distributed power.
Higher efficiency - reduced CO2 emission.
Remains quiet operation.

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